

BVRI photometry of 53 unusual asteroids

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ABSTRACT

We present the results of *BVRI* photometry and classification of 53 unusual asteroids, including 35 near-Earth asteroids (NEAs), 6 high eccentricity/inclination asteroids, and 12 recently-identified asteroid-pair candidates. Most of these asteroids were not reportedly classified prior to this work. For the few asteroids that have been previously studied, the results are generally in rough agreement. In addition to observe and classify these objects, we merge the results from several photometric/spectroscopic surveys to create a largest-ever sample with 449 spectrally classified NEAs for statistical analysis. We identify a “transition point” of the relative number of C/X-like and S-like NEAs at $H \sim 18 \Leftrightarrow D \sim 1\text{km}$ with confidence level at $\sim 95\%$ or higher. We find that the C/X-like:S-like ratio for $18 \leq H < 22$ is about two times higher than that of $H < 18$ (0.33 ± 0.04 versus 0.17 ± 0.02), virtually supporting the hypothesis that smaller NEAs generally have less weathered surface (therefore, less reddish appearance) caused by younger collision ages.

Subject headings: Techniques: photometric – Minor planets, asteroids: general

1. Introduction

The origin of unusual asteroid groups such as the near-Earth asteroids (NEAs) and paired-asteroids (Vokrouhlický & Nesvorný 2008; Pravec & Vokrouhlický 2009) has raised many research interests over the recent years. A good way to understand this matter is to spectrally classify as many individuals as possible (e.g. Binzel et al. 1996). Since the 1980s, about a dozen of photometric and spectroscopic surveys aiming at determining taxonomic distributions of asteroids of different categories have been carried out (Table 1) and derived spectral classifications for a few hundreds of NEAs as the result. However, among the $> 7,500$ known NEAs, high eccentricity/inclination asteroids, and a few dozens proposed paired-asteroid candidates, the fraction of reportedly classified objects is still small (around 5%), the fraction is even lower ($\sim 1\%$) for those with measured physical characteristics (albedo, diameter, mineralogy, etc.).

Recent studies have suggested that the characteristics of sub-kilometer-size NEAs may be very different from that of kilometer-size NEAs (see Trilling et al. 2010, for an overview), and a sign that has been noted for a decade is the tendency of overabundance of C/X-like (or neutral colored) asteroids among small size NEAs (Rabinowitz 1998). Comparing with other issues, which generally require fine spectroscopic information and albedo measurement, the issue of overabundance of small C/X-like asteroids is relatively easy to work on, since only crude classification is required. However, confirmation is unable to be made by previous studies (such as Dandy et al. 2003; Binzel et al. 2004) due to the lack of data of sub-kilometer-size NEAs.

On the other hand, the recently identified paired-asteroid candidates are likely to be of common origin (Pravec & Vokrouhlický 2009). It could be a convincing evidence to support this hypothesis if both components within a pair are proved to have identical classification, but however physical observations are lacking for almost

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all paired-asteroid candidates until now.

The method combining visual/near-infrared spectroscopy and thermal infrared measurement is preferred among all practical ground-based methods as it provides highest accuracy as well as most complete information of a target in most cases, but however it is also very time consuming and generally requires medium or large telescopes. By contrast, broad-band *BVRI* photometry only allows crude classification, but it is more efficient than spectroscopy as it does not require as much times and efforts as the latter, and the result can be useful for preliminary diagnose purpose. In this study, we employed this method to investigate some selected unusual asteroids. Most of these asteroids had not been reportedly classified prior to the observational phase of this work. Description of the observation procedure, data reduction and details of classification is presented in Section 2 and 3. We then compared and merged our results with other reported studies to assess the result consistency between ours and others (Section 4.1) and investigate the degrees of consistency with theoretical expectations (Section 4.2 and 4.3).

2. Observation

The Lulin One-meter Telescope (LOT) at Lulin Observatory, Taiwan, was employed for this study, except for one asteroid, 2008 EV5, which was observed with the 0.41-m telescope of the same observatory. The 0.41-m telescope observations for 2008 EV5 were made in January 2009 with the 2048×2048 U42 CCD, while the LOT observations were all made during the observation runs in the dark period of January 2010 except (143651) 2003 QO104, which was observed in April 2009, with the 1340×1300 PI-1300B CCD and a $0.5\times$ focal reducer. A broad-band Bessell *BVRI* filter system was used on both telescopes, with the wavelengths centered at 442, 540, 647 and 786 nm respectively.

Landolt standard stars (Landolt 1992) are preferred in optical photometry because they can guarantee highest accuracy (better than 0.01-0.02 mag) in most cases. However, as Landolt standard stars are only available to a very limited region, in most occasions one needs to know the atmospheric extinction coefficient by observing standard stars in different airmass to work on targets

locate far from Landolt fields. As we were unable to observe sufficient Landolt standard stars to get a secure extinction coefficient through every observing night, an alternative approach introduced by Warner (2007) is employed. Warner applied third-order polynomials on his optical observations of 128 carefully-chosen Landolt standard stars to find the conversion terms between the 2MASS *JHK* system (Skrutskie et al. 2006) and the Landolt system, the errors of Warner's method are 0.034 for $B-V$ and $V-I$ and 0.021 for $V-R$ as indicated in his paper. The field-of-view for LOT and the 0.41-m telescope are $22' \times 22'$ and $47' \times 47'$ respectively, which are large enough to include sufficient 2MASS catalog stars for setting up a good in-field transformation. To assess the accuracy of Warner's method, we observed a few stars in M67 (NGC 2682) and derived their colors following the procedure described by Warner, then compared them with another high precision *VRI* photometry (Taylor et al. 2008). The resulting accuracy is better than 0.02 mag in $V-R$ and $V-I$ (Table 2).

The targets are all observed with an airmass of $X \leq 2$ with the predicted visual magnitude brighter than 19.0. Observational details as well as basic information of each target are shown in Tables 3 and 4 as for NEAs/high eccentricity (inclination) objects and paired-asteroid candidates. The exposure sequence for all targets is *B-R-V-I* to minimize the error produced by significant brightness variation. Image frames are then bias-subtracted and flat-fielded, and the fringing effects in *I*-band images are also removed.

The raw observations are then inspected manually to exclude the bad cases, such as the target asteroid crossing over or passing very close to background stars, or low signal-to-ratio (SNR) caused by unstable weather conditions. Photometric measurements are then performed with Warner's software *MPO Canopus*. At least ten background stars with known 2MASS magnitudes are used to derive the transformation coefficient between instrumental magnitude and standard magnitude for each field. In very few cases, the limited number of background stars cannot guarantee a good transform to be derived, so the coefficients derived from observations obtained in the same night with a similar airmass ($\Delta X < \sim 0.05$) are used instead. Although each target was planned to be observed

3-5 times, various reasons (such as target/star encounter, unstable weather, and/or instrument problems) may prevent us to do so, and for some targets only one observation of each filter was obtained. These results shall be used with care.

3. Classification

Observations of 53 asteroids were obtained and reduced following the procedure described in Section 2, including 35 NEAs¹, 6 high eccentricity/inclination asteroids, and 12 main-belt paired-asteroid candidates. The objects are then classified using the Dandy et al. (2003)’s derivation of the Tholen taxonomy (Tholen 1984), intent for optical broad-band photometry². We note that the spectral appearances of C-, B-, F-, G- and X-class are fairly close, making it difficult to classify them uniquely by broad-band photometry, so all objects with colors similar to these classes are considered as X-class. The only exception is that the object shown to be particularly blue ($B - V \ll 0.75$) and can be tentatively considered as B-class with some confidence.

For each object, the second central moment about the $B - V$, $V - R$ and $V - I$ magnitudes from the typical colors for each taxonomic class are computed, and the class with minimum second central moment is assigned as the object’s class. In some cases, the error range of the colors have covered more than one class and/or the second central moment of several classes are very close, so multiple classes are assigned to this object with the first class being most probable. In two cases [(13732) Woodall and (228747) 2002 VH3], only a very crude classification (C/X-like or S-like) can be made due to low-quality observations (see Section 4.3 for details). When the second central moment of the most probable class for a particular object is large ($\sim > 0.003$), a “(u)” (uncertain) is

appended to indicate that this classification may be uncertain.

The colors and the classifications for the observed NEAs/high eccentricity (inclination) asteroids and paired-asteroid candidates observed in this study are shown in Table 5 and Table 6 respectively. Classification and/or albedo measurement from previous work is also given if available. We note that a total of four objects were observed in different nights, color measurements across these nights with different calibration stars are found to be consistent. Measurements from each night are listed separately illustrate the accuracy and consistency of our work.

4. Discussion

4.1. Comparisons with previous works on NEA colors

Following the procedure described in Section 2 and 3, we have derived color indices and classifications for 35 NEAs, including 17 Amors, 13 Apollos and 5 Atens. Among the sample, a total of eight NEAs were reportedly classified by previous surveys; it has been found that our classifications are generally consistent with them. In addition, we note that a total of six NEAs in our sample were also observed by recently-conducted Warm-Spitzer program (Trilling et al. 2010), with uncertainties around a factor of 2 unless otherwise specified (see Section 5.3.4 of their paper). Although Warm-Spitzer derives albedo of the NEAs and does not classify them directly, its observation can be a good addition to broad-band photometry, especially when the classification is ambiguous. Each case of these cross-observed NEAs is discussed below.

(5604) 1992 FE The $V - R$ and $V - I$ colors measured from our observation suggested V-, Q-, C- or R-type classification, with V-type to be most likely. This is consistent with the classification made by Binzel et al. (2004) in spectroscopy. Albedo measurement by Delbó et al. (2003) and Warm-Spitzer observation (Trilling et al. 2010) also suggest a high albedo that support a V-type classification.

¹We have also obtained BV magnitude for (143947) 2003 YQ117 and $BVRI$ magnitude for (214088) 2004 JN13, suggesting R/S and A-type classification for these two objects, but however as the raw images suffered from bad seeing conditions resulting in uncertainty at the level of 0.2 mag, so these two measurements are excluded in our formal result.

²It should be noted that Dandy et al.’s derivation was used for their KPNO B and Harris VRI filter system, which is slightly different (the differences on wavelength centers are up to 2.5%) from the Bessell $BVRI$ system applied in this study.

(5653) Camarillo The S- and Sq-type classification suggested by Dandy et al. and de León et al. (2010) are consistent with the S-type classification suggested by our observation.

(21088) 1992 BL2 de León et al. suggested a Sl-type classification which is consistent with the S-type classification suggested by our observation.

(38086) Beowulf Warm-Spitzer reported an albedo of 0.37 for this object. This is a rough match to our R-type classification according to the debiased mean albedo estimates for R-type NEAs given by Stuart & Binzel (2004), which is 0.340. However, we need to point out that Stuart & Binzel was actually using the average albedo of main-belt asteroids derived from the work of Tedesco et al. (2002), as no albedo measurements of any R-type NEAs had been reported (See Section 1.4, Paragraph 3 and Footnote 1 in their paper for details), hence this comparison can be misleading.

(54789) 2001 MZ7 Near-infrared spectroscopy by Lazzarin et al. (2005) reported (54789) 2001 MZ7 to be an X-complex asteroid while *BVRI* photometry by Betzler et al. (2010) suggested G-type classification. These two results are consistent with the X-type classification made in this study, since the degenerate X-type includes the C and G types. The color indices we measured also match with Betzler et al.'s within 0.03 mag.

(56048) 1998 XV39 Our observation suggested an R-type classification while Sa-type suggested both by Lazzarin et al. and de León et al. by spectroscopy. We note that (56048) 1998 XV39 appears redder than typical S-type asteroids in our observation (0.770 ± 0.045 in $V - I$ magnitude versus the criteria of 0.889). As the redness of Sa-type asteroid is more close to that of R-type asteroid than to typical S-type asteroid (see DeMeo et al. 2009, Figure 15), it can be considered that our observation is in good consistency with the two spectroscopic observations.

(137805) 1999 YK5 Our observation suggested an R- or Q-type classification which is in-

consistent with the X-type classification by Binzel et al. by spectroscopy.

(137925) 2000 BJ19 Our observation of this object suffered from low SNR, so the colors we measured cannot distinguish it from S-, T- or D-type classification, with S-type to be most likely. Binzel et al. suggested a Q-type classification for this object by spectroscopy, which is consistent with our S-type suggestion.

(138937) 2001 BK16 Our observation showed that (138937) 2001 BK16 to be slightly blue, with $B - V = 0.648 \pm 0.067$. Since the upper limit allowed by our error is $B - V = 0.71$, which is within the range of X-class, we classify this object as X rather than the rare B-type. Warm-Spitzer observation yielded an albedo of 0.2, which can barely be matched with the albedo estimates for C- or X-type (debiased mean albedo of 0.101 for C-type and 0.072 for X-type as given by Stuart & Binzel).

(143651) 2003 QO104 Our observation suggested an R-type classification for (143651) 2003 QO104, this is consistent with the S-type suggested by Hicks and R- or S-type suggested by Betzler et al. (see Betzler et al. 2010). The color indices we measured matched with Betzler et al.'s within 0.02 mag. On the other hand, Warm-Spitzer observation indicated an albedo of 0.13 for this object. Considering the debiased mean albedo for R- and S-type NEAs given by Stuart & Binzel to be 0.340 and 0.239 respectively, an S-type classification for this object might be more appropriate. However, as have mentioned earlier, we do not know the *true* mean albedo for R-type NEAs, so the exact classification for this object is still an open question at this moment.

(159402) 1999 AP10 Our observation suggested S-type classification for this object, but there is a ~ 0.1 mag difference in $B - V$ magnitude from the typical color. Meanwhile, it has been reported that (159402) 1999 AP10 to be an L or S-type asteroid (Betzler et al. 2010) by spectroscopy and broad-band photometry. The difference between our and Betzler et al.'s observation of $B - V$ magnitude is about 0.12 mag, while $V - R$ and $V - I$ colors matched to 0.02

mag. Warm-Spitzer program gave an albedo estimate of 0.34, which does not oppose our S-type suggestion as the mean albedo for S-type NEAs was found to be 0.239 by Stuart & Binzel. In addition, the error bar σ for mean albedo determination of S-type NEAs is ± 0.044 as given by the authors, corresponding to an average dispersion of ± 0.15 considering there are 12 S-type NEAs used to determine the mean³, we can see that the Warm-Spitzer measurement mostly overlaps the albedo range of S-type NEAs.

(162998) 2001 SK162 The $B - V$ and $V - R$ magnitudes derived from our observation suggested X- or V-type classification, while X-type is more likely. There is a rough consistency between our X-type suggestion and Binzel et al.’s T-type classification.

2002 LV Our observation suggests an X- or Q-type classification for this object, with Q-type to be more likely. On the other hand, observation from Warm-Spitzer suggested an albedo of 0.15. This does not resolve the ambiguity, since the uncertainty range covers the mean albedos for C-, X-, and Q-type NEAs by Stuart & Binzel, which is 0.101, 0.072, and 0.247 respectively. However, considering that the average dispersions for each of the three complexes are 0.06, 0.06 and 0.15 respectively, we may conclude that a Q-type classification is the most probable classification for this object, since the uncertainties from both sources could have largest intersection under such a justification.

2007 MK13 Colors derived from our observation fall between the typical colors of X- and T-type asteroids, with X-type classification to be more likely. Considering we have combined C- and X-class together, our classification is consistent with Hicks & Somers (2010)’s C-type classification.

³As calculated by $D(x) = \sigma\sqrt{N-1}$ where $D(x)$ is the average dispersion.

4.2. Statistical analysis with the results from other photometric and spectroscopic surveys

To compare the similarities and differences between the results of some recently-conducted photometric and spectroscopic NEA surveys, we include the results from several surveys as listed in Table 1, including de León et al. (2010), SINEO (Lazzarin et al. 2005), SMASS (Bus & Binzel 2002; Binzel et al. 2004), Dandy et al. (2003), and Angeli & Lazzaro (2002)⁴. The classification results are firstly consolidated into several taxonomic complexes based on the scheme suggested by Binzel et al. (2004) to allow the fractional abundances detected by each survey to be comparable (Table 7). In addition, the taxonomic complexes are further consolidated into two general categories, “C/X-like”⁵ and “S-like”, in order to determine the ratio of C/X-like and S-like observed by each survey. Considering the definition by Morbidelli et al. (2002)⁶, we consider the asteroids of class A, O, Q, R, S, U, and V as “S-like” while the asteroids of class C and D as “C/X-like”. The degeneracy of X-complex is a problem since it includes members with diverse physical properties. As we don’t have the fine physical data for each X-complex member, we consider the assumption of a dark-to-bright ratio (equivalent with our C/X-like:S-like ratio, as we have argued and presumed above) of 0.45 among X-complex

⁴The result of Fevig & Fink (2007) is excluded as they are using a different taxonomy than Tholen’s or Bus-DeMeo’s.

⁵We see the need to use the “C/X-like” concept, instead of the “C-like” concept as used in many other papers to-date, to avoid interference over the “dark/bright” issue (which should primary rely on albedo information), although these two concepts are, in fact, equivalent with each other.

⁶The classification method applied by Morbidelli et al. is actually dividing the asteroids into “dark” (corresponding to the “C/X-like” group in our study) and “bright” (corresponding to the “S-like” group in our study). However, some NEAs in their sample were classified based on taxonomic classification rather than real albedo. As the correlation between spectroscopic information and the target’s albedo is still not well understood, we still apply a “C/X-like versus S-like” pattern that emphasizing the trend in color rather than a “dark-bright” pattern that emphasizes albedo. To simplify our following discussions, we also consider the results coming from a “dark-bright” pattern (as applied by the studies mainly based on spectroscopic data, such as Morbidelli et al.’s and Binzel et al.’s) to be quantitatively equivalent with the results from “C/X-like versus S-like” pattern.

NEAs as given by Binzel et al. (2004) base on the albedo-taxonomy correlation of 22 X-complex NEAs. For the two photometric surveys (ours and Dandy et al.’s), things are more complicated since C- and X-complex cannot be distinguished, so we consider the relative number of C- and X-complex members among NEAs to be ~ 0.5 as determined by Binzel et al., resulting a C/X-like:S-like ratio of $(0.5 + 0.45)/(1 - 0.45) \approx 1.73$ in the combined C- and X-complex for the two photometric surveys. Finally, the objects with several possible classifications are excluded to avoid inducing further uncertainty.

As illustrated in Table 8, the surveys agree on a dominate position of silicate composed asteroids (Q-, R-, S- and V-type). The fractions of each complex tend to be close on a larger sample n , suggesting that the fraction differences among the surveys are primary caused by random errors in observational sampling.

An interesting feature to look at is that the C/X-like:S-like ratio appeared to be magnitude dependent. The surveys with $\overline{H} < 17$ (de León et al.’s, Michelsen et al.’s, and Angeli & Lazzaro’s) all have the ratio smaller than 0.1, while the others all have the ratio larger than 0.1, suggesting a trend of more C/X-like asteroids at a larger H (smaller size). This phenomenon has been noted by Rabinowitz (1998), Morbidelli et al. (2002), Dandy et al. (2003) and Binzel et al. (2004), but no decisive conclusion were carried out due to lack of data among large H (small size) asteroids. By contrast, Morbidelli et al. suggested that the ratio should slightly decrease with a larger H due to observational bias effect and base on model prediction (see Section 2 of their paper), which is opposed to the implication of Table 8.

To investigate this matter further, we merge all data together, creating a large dataset with 449 NEAs (with 434 NEAs with $H \leq 22$ and 382 NEAs with $H \leq 20$), and grouped them into one-magnitude-wide bins. For each magnitude bin, the C/X-like:S-like ratio is computed base on the scheme described above. The result is listed in Table 9.

Comparing the result with Morbidelli et al.’s study, which has included 183 NEAs with $H < 20$, the ratio variation from magnitude to magnitude between the two studies is similar: a lower C/X-like:S-like ratio on $H < 18$ and a higher ratio on

$H \geq 18 \Leftrightarrow D \leq 1\text{km}$, which agrees the implication of Table 8. To check the statistical significance of this phenomenon, we divide the whole sample into two groups by an $H = 18$ cutoff, with the sample n of each group to be 246 ($H < 18$) and 203 ($H \geq 18$) respectively, and perform a χ^2 test on the two groups. It has been shown that the distributions of two groups are different at a confidence level of 99.5%, which is large enough to be considered as statistically significant. Although our treatment of the C/X-like:S-like ratio of the X-complex may induct some uncertainty, we note that even we consider a 1σ uncertainty of the numbers of X-complex members to be “C/X-like” (assuming random observation errors) for both $H < 18$ and $H \geq 18$, for which the numbers of X-complex members considered as “C/X-like” would be 10 ± 3 and 17 ± 4 respectively, the minimum possible confidence level is still shown to be $\sim 95\%$. What is more, we notice that the C/X-like:S-like ratio we derived is 0.17 ± 0.02 for NEAs with $H < 18$, which is in a good match of the model prediction of 0.18 according to Morbidelli et al, implying our treatment of the X-complex members with $H < 18$ would lead to a good match with the model. However, things are no longer that case when it comes to an $H < 20$ cutoff line, for which our estimate of the C/X-like:S-like ratio is shown to be 0.22 ± 0.02 , about 3-7% higher than Morbidelli et al.’s model prediction (0.17). It is noteworthy that we have to consider *all* X-complex members with $18 \leq H < 20$ to be “S-like” as in an extreme situation for a compatible ratio with the model prediction (0.18 versus the model’s 0.165 ± 0.015). In addition, our estimate of C/X-like:S-like ratio for $18 \leq H < 22$ (sample $n = 187$ comparing with $n \sim 50$ for $18 \leq H < 20$ in Morbidelli et al.’s sample) is 0.33 ± 0.04 . In all, it is plausible to say that a transition point of C/X-like:S-like ratio exists at $H = 18$ in our sample, which is consistent with the hypothesis that small asteroids generally have younger collision age and tend to be less weathered (thus, less reddish/neutral colored) than large ones (Binzel et al. 1998), hence leads to the overabundance of C/X-like asteroids in small NEAs.

Morbidelli et al. suggested a factor of ~ 1.4 between observed and true C/X-like:S-like ratio caused by the phase angle effect at discovery. Assuming that this number remains quasi-constant

for different H , we will get a true C/X-like:S-like ratio of 0.24 for asteroids with $H < 18$, which is in a good match with Morbidelli et al.'s model (0.25 ± 0.02). However, for $H \geq 18$, the true ratio can be as high as 0.5 in our sample.

4.3. Discussion of the paired-asteroid candidate observations

Because of the constraints of the target observability, only two pairs were with both components observed, they are (1979) Sakharov vs. (13732) Woodall and (11842) Kap'bos vs. (228747) 2002 VH3 respectively. Unfortunately, we were unable to obtain complete color indices for either pairs: for the first pair, (13732) Woodall is suffered from instrument problems so the $V - I$ magnitude is missing, while (228747) 2002 VH3 was just passing near a 4.5 mag star when the observation was taken for the second pair, so we are only able to make a very crude classification for these two objects. In general, both components of both pairs are classified as S-like asteroid, providing a weak evidence of the common-origin hypothesis as expected.

5. Conclusion

Our efforts have added the spectral data of some tens of interesting asteroids into knowledge. For the few asteroids that had been reportedly classified, our results are generally in rough agreement, indicating the goodness of our work.

Further to observing and classifying the asteroids, we also examined the matter of overabundance of C/X-like (neutral colored) asteroids among small size NEAs, a phenomenon that had previously been noted by several studies without a decisive conclusion. In a largest-ever sample we created from merging results from several photometric/spectroscopic surveys with 449 spectrally classified NEAs in total, we identify a "transition point" of the C/X-like:S-like ratio among NEAs at $H \sim 18 \Leftrightarrow D \sim 1\text{km}$ with statistical confidence level at 95% or higher. The C/X-like:S-like ratio for NEAs with $H < 18$ is estimated to be 0.17 ± 0.02 as measured in this sample, which is in good match with previous model prediction by Morbidelli et al.; while the ratio for NEAs with $18 \leq H < 22$ is estimated to be 0.33 ± 0.04 , about two times higher than that for $H < 18$ and be-

ing inconsistent with model prediction. However, this finding supports the hypothesis that asteroids with less reddish appearances are more abundant among small size NEAs than large ones due to younger collision ages and less weathered surface.

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TABLE 1
SOME PHOTOMETRIC/SPECTROSCOPIC NEA SURVEYS CONDUCTED OVER THE RECENT DECADE

Publication	Observation period	NEA sample size	Method
de León et al. (2010)	2002-2007	77	VIS/NIR ^a spectroscopy
Fevig & Fink (2007)	1997-1998, 2004	55	VIS ^b spectroscopy
Michelsen et al. (2006)	2003	12	VIS spectroscopy
SINEO (Lazzarin et al. 2005)	2002-2004	36	VIS/NIR spectroscopy
SMASS (Binzel et al. 2004; Bus & Binzel 2002)	1994-2002	310	VIS spectroscopy
Dandy et al. (2003)	2000-2001	56	Broad-band <i>BVRIZ</i> photometry
S^3OS^2 (Angeli & Lazzaro 2002)	1996-2001	12	VIS spectroscopy

^aVIS stands for visual channel (about 390-750nm) while NIR stands for near-infrared channel (about 700-3,000nm)

^bAlthough the study is labeled as visual and near-infrared spectroscopy in the publication, it only covers the near-infrared channel to 1,000nm, so it is considered as visual spectroscopy in this summary.

TABLE 2
COMPARISON ON THE VRI PHOTOMETRY OF M67 (NGC 2682) BETWEEN THIS WORK AND
TAYLOR ET AL. (2008)

Star	$V - R$ by Taylor et al.	$V - I$ by Taylor et al.	Date observed	Airmass	$V - R$ by this study	$V - I$ by this study
NGC 2682 F132	0.350 ± 0.003	0.679 ± 0.006	2010-01-12	1.69	0.336 ± 0.011	0.676 ± 0.023
			2010-01-13	1.34	0.342 ± 0.003	0.677 ± 0.007
NGC 2682 I51	0.336 ± 0.003	0.671 ± 0.007	2010-01-12	1.69	0.331 ± 0.016	0.651 ± 0.024
			2010-01-13	1.34	0.334 ± 0.007	0.655 ± 0.010

TABLE 3
OBSERVATIONAL DETAILS OF THE OBSERVED NEAS AND HIGH ECCENTRICITY/INCLINATION OBJECTS

Object	H	Orbit	Date observed	V_{obs}	Exp. time	Cycle	Tot. time
(5604) 1992 FE	16.4	ATE	2010-1-13	19.4	60s	5	40min
(5653) Camarillo	15.4	AMO	2010-1-13	18.5	60s	5	40min
(16868) 1998 AK8	16.6	UNU	2010-1-13	17.3	30s	3	16min
(20898) Fountainhills	11.0	UNU	2010-1-8	14.7	60s	5	39min
(21088) 1992 BL2	14.2	AMO	2010-1-8,13	17.4,17.4	60s,60s	5,5	39min,40min
(24761) Ahau	17.4	APO	2010-1-8	15.6	20s	3	15min
(35432) 1998 BG9	19.3	AMO	2010-1-13	18.9	30s	3	24min
(38086) Beowulf	17.1	APO	2010-1-13	18.2	30s	2	11min
(54789) 2001 MZ7	14.8	AMO	2010-1-8	14.6	30s	5	30min
(66251) 1999 GJ2	17.0	AMO	2010-1-13	18.2	90s	2	18min
(68216) 2001 CV26	16.3	APO	2010-1-8	17.6	30s	3	22min
(86067) 1999 RM28	16.4	AMO	2010-1-8	17.1	30s	3	17min
(96177) 1984 BC	16.0	UNU	2010-1-13	17.7	2min	5	58min
(99248) 2001 KY66	16.2	APO	2010-1-13	19.0	90s	4	39min
(103067) 1999 XA143	16.6	APO	2010-1-8	16.8	30s	5	30min
(122180) 2001 KV43	17.3	AMO	2010-1-10,12	18.1,18.3	3min,3min	5,2	56min,37min
(137805) 1999 YK5	16.6	ATE	2010-1-8	17.5	30s	5	30min
(137925) 2000 BJ19	15.8	APO	2010-1-10,12	19.0,18.7	60s	5,5	22min,14min
(138937) 2001 BK16	17.3	APO	2010-1-10,12	17.4,17.7	30s,30s	5,3	22min,7min
(143651) 2003 QO104	16.0	AMO	2009-4-24	16.6	60s	9	59min
(152742) 1998 XE12	19.1	ATE	2010-1-10,12	18.2,18.0	30s,30s	5,5	22min,14min
(159402) 1999 AP10	16.0	AMO	2010-1-8	15.7	30s	5	30min
(162566) 2000 RJ34	15.2	AMO	2010-1-12	18.9	60s	5	39min
(162998) 2001 SK162	17.9	AMO	2010-1-10	18.6	60s	3	17min
(230111) 2001 BE10	19.1	ATE	2010-1-10,12	17.7,17.7	20s,20s	1,3	2min,28min
2002 LV	16.6	APO	2010-1-9	18.1	60s	5	40min
2003 SM4	15.4	UNU	2010-1-9	19.0	90s	3	28min
2004 NZ8	16.1	UNU	2010-1-9	18.3	2min	5	58min
2004 TB18	17.8	APO	2010-1-12	18.2	20s	4	21min
2004 XD50	18.5	AMO	2010-1-9	17.6	30s	4	24min
2005 EN36	17.2	UNU	2010-1-8,9	17.5,17.5	2min,2min	1,5	6min,58min
2005 MC	16.6	AMO	2010-1-8	16.5	30s	3	18min
2006 UR	19.4	AMO	2010-1-8	16.4	30s	2	11min
2006 YT13	18.4	APO	2010-1-10	18.1	20s	5	20min
2007 MK13	20.0	APO	2010-1-8	17.2	30s	3	43min
2007 UR3	21.2	AMO	2010-1-9	17.7	60s	5	39min
2008 EV5	20.0	ATE	2009-1-4	14.7	20s	5	10min
2008 YZ32	20.1	APO	2010-1-9	17.3	20s	5	15min
2009 UV18	16.0	AMO	2010-1-9	18.3	30s	5	30min
2009 XR2	18.6	AMO	2010-1-9	16.5	30s	3	17min
2010 AE30	23.6	APO	2010-1-9	18.5	60s	2	39min

TABLE 3—*Continued*

Object	H	Orbit	Date observed	V_{obs}	Exp. time	Cycle	Tot. time
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NOTE.—The absolute magnitude H for each object is obtained from the Minor Planet Center Orbit Database (MPCORB). The orbit types are classified as follows: Main-belt Asteroids (MBA), Atens (ATE), Apollos (APO), and Amors (AMO). Asteroids with $e > 0.4$ and/or $i > 40^\circ$ but not fall into the category of NEAs ($q < 1.3$) are classified as unusual objects (UNU). The visual magnitude V_{obs} given here is the mean value of the V -band observations.

TABLE 4
OBSERVATIONAL DETAILS OF THE OBSERVED PAIRED-ASTEROID CANDIDATES

Object	H	Companion	Date observed	V_{obs}	Exp. time	Cycle	Tot. time
(1979) Sakharov	13.5	(13732) Woodall ^a	2010-1-12,13	18.8,18.8	90s,90s	1,1	7min,5min
(2110) Moore-Sitterly	13.8	(44612) 1999 RP27	2010-1-10	18.4	2min	5	42min
(4765) Wasserburg	14.1	2001 XO105	2010-1-9	16.9	60s	3	23min
(5026) Martes	12.9	2005 WW113	2010-1-10	18.6	60s	1	11min
(11842) Kap'bos	13.8	(228747) 2002 VH3 ^a	2010-1-9	18.5	60s	5	39min
(13732) Woodall	14.4	(1979) Sakharov ^a	2010-1-10	18.7	90s	4	29min
(15107) Toepperwein	14.3	2006 AL54	2010-1-10,12	18.5,18.5	2min,2min	5,2	43min,9min
(25884) 2000 SQ4	14.6	(48527) 1993 LC1	2010-1-10	18.5	150s	2	14min
(52852) 1998 RB75	14.6	2003 SC7	2010-1-12	18.7	5min	5	115min
(54041) 2000 GQ113	14.5	2002 TO134	2010-1-10	18.6	2min	2	12min
(56048) 1998 XV39	15.0	(76148) 2000 EP17	2010-1-10,12	17.4,18.4	3min,3min	5,5	54min,37min
(228747) 2002 VN3	16.5	(11842) Kap'bos ^a	2010-1-9	18.8	2min	3	33min

NOTE.—The absolute magnitude H for each object is obtained from the Minor Planet Center Orbit Database (MPCORB). The visual magnitude V_{obs} given here is the mean value of the V -band observations.

^aThe companion of this object is also observed in this study.

TABLE 5
PHOTOMETRY AND CLASSIFICATION RESULTS OF OBSERVED NEAs AND HIGH
ECCENTRICITY/INCLINATION OBJECTS

Object	Date observed	V_{obs}	Class (this work)	Previous class	$B - V$	$V - R$	$V - I$	Albedo
(5604) 1992 FE	2010-1-13	19.4	VQXR	V ^a		0.439 ± 0.077	0.679 ± 0.083	0.38-0.69 ^b
(5653) Camarillo	2010-1-13	18.5	S	Sq ^c	0.985 ± 0.062	0.465 ± 0.050	0.893 ± 0.048	
(16868) 1998 AK8	2010-1-13	17.3	S		0.908 ± 0.031	0.443 ± 0.014	0.857 ± 0.002	
(20898) Fountainhills	2010-1-8	14.7	X		0.767 ± 0.008	0.428 ± 0.010	0.826 ± 0.008	
(21088) 1992 BL2	2010-1-8	17.4	S	SI ^c	0.972 ± 0.048	0.490 ± 0.006	0.913 ± 0.015	
	2010-1-13	17.4			0.919 ± 0.055	0.438 ± 0.014	0.907 ± 0.028	
(24761) Ahau	2010-1-8	15.6	S		0.835 ± 0.023	0.469 ± 0.008	0.872 ± 0.002	0.37 ^b
(35432) 1998 BG9	2010-1-13	18.9	A			0.547 ± 0.030	0.913 ± 0.045	
(38086) Beowulf	2010-1-13	18.2	R(u)		0.999 ± 0.020	0.447 ± 0.018	0.645 ± 0.098	
(54789) 2001 MZ7	2010-1-8	14.6	X	X ^d , G ^e	0.707 ± 0.011	0.389 ± 0.004	0.711 ± 0.002	
(66251) 1999 GJ2	2010-1-13	18.2	S	Sa ^c , Sa ^e	0.976 ± 0.088	0.448 ± 0.036	0.844 ± 0.021	
(68216) 2001 CV26	2010-1-8	17.6	R		0.916 ± 0.036	0.479 ± 0.007	0.811 ± 0.025	
(86067) 1999 RM28	2010-1-8	17.1	S(u)		0.996 ± 0.069	0.499 ± 0.018	0.881 ± 0.021	
(96177) 1984 BC	2010-1-13	17.7	S		0.864 ± 0.045	0.484 ± 0.018	0.921 ± 0.019	
(99248) 2001 KY66	2010-1-13	19.0	ST		0.865 ± 0.048	0.455 ± 0.041	0.998 ± 0.072	
(103067) 1999 XA143	2010-1-8	16.8	S		0.925 ± 0.029	0.458 ± 0.011	0.878 ± 0.009	
(122180) 2001 KV43	2010-1-10	18.1	S		0.894 ± 0.067	0.508 ± 0.036		
	2010-1-12	18.3					0.915 ± 0.072	
(137805) 1999 YK5	2010-1-8	17.5	RQ	X ^a	0.908 ± 0.035	0.390 ± 0.051	0.704 ± 0.036	
(137925) 2000 BJ19	2010-1-10	19.0	STD	Q ^a	0.756 ± 0.135	0.508 ± 0.079		
	2010-1-12	18.7					0.915 ± 0.072	
(138937) 2001 BK16	2010-1-10	17.4	X		0.648 ± 0.067	0.369 ± 0.034		0.21 ^b
	2010-1-12	17.7					0.565 ± 0.082	
(143651) 2003 QO104	2009-4-24	16.6	R	RS ^e	0.903 ± 0.008	0.454 ± 0.011	0.797 ± 0.019	
(152742) 1998 XE12	2010-1-10	18.2	RS		0.898 ± 0.100	0.460 ± 0.062		0.34 ^b
	2010-1-12	18.0					0.825 ± 0.043	
(159402) 1999 AP10	2010-1-8	15.7	S(u)	S ^f	0.983 ± 0.023	0.485 ± 0.007	0.868 ± 0.009	
(162566) 2000 RJ34	2010-1-12	18.9	X		0.755 ± 0.136	0.400 ± 0.032	0.836 ± 0.047	
(162998) 2001 SK162	2010-1-10	18.6	XV	T ^a	0.822 ± 0.139	0.386 ± 0.018		
(230111) 2001 BE10	2010-1-10	17.7	R		0.929	0.420		0.15 ^b
	2010-1-12	17.7			0.982 ± 0.087	0.496 ± 0.035	0.870 ± 0.095	
2002 LV	2010-1-9	18.1	QX		0.772 ± 0.144	0.425 ± 0.039	0.719 ± 0.046	
2003 SM4	2010-1-9	19.0	V			0.387 ± 0.052	0.602 ± 0.055	
2004 NZ8	2010-1-9	18.3	X		0.704 ± 0.085	0.404 ± 0.027	0.707 ± 0.028	
2004 TB18	2010-1-12	18.2	AS			0.510 ± 0.084	1.000 ± 0.138	
2004 XD50	2010-1-9	17.6	R		0.927 ± 0.030	0.458 ± 0.005	0.791 ± 0.025	
2005 EN36	2010-1-8	17.5	X		0.701	0.356	0.697	
	2010-1-9	17.5			0.737 ± 0.016	0.369 ± 0.010	0.681 ± 0.014	
2005 MC	2010-1-8	16.5	X		0.752 ± 0.022	0.413 ± 0.010	0.766 ± 0.010	
2006 UR	2010-1-8	16.4	R		0.969 ± 0.097	0.434 ± 0.060	0.754 ± 0.053	
2006 YT13	2010-1-10	18.1	AR		1.042 ± 0.088	0.475 ± 0.057		
2007 MK13	2010-1-8	17.2	XT	C ^f	0.783 ± 0.016	0.414 ± 0.010	0.838 ± 0.019	
2007 UR3	2010-1-9	17.7	X		0.631 ± 0.054	0.381 ± 0.025	0.603 ± 0.044	
2008 EV5	2009-1-4	14.7	X		0.722 ± 0.033	0.363 ± 0.010	0.702 ± 0.010	
2008 YZ32	2010-1-9	17.3	B		0.535 ± 0.032	0.207 ± 0.055	0.507 ± 0.012	

Table 7: Summary of consolidated taxonomic classes bases on the works of Binzel et al. (2004) and Stuart & Binzel (2004)

Taxonomic complex	Includes
A	A
C	C, Cb, Cg, Cgh, Ch, B, F, G
D	D,T
O	O
Q	Q, Sq
R	R
S	S, Sa, Sk, Sl, Sr, Sv, K, L, Ld
U	U
V	V
X	X, Xc, Xe, Xk, E, M, P

Table 9: Counts of C/X-like, S-like, or X-complex categories in each magnitude bins as well as the corresponding C/X-like:S-like ratio

Mag bin	C/X-like	S-like	X-complex (numbers assigned to C/X-like)	C/X-like:S-like ratio
< 14.00	1	11	0(0)	0.09
14.00-14.99	3	19	5(2)	0.23
15.00-15.99	1	43	3(1)	0.04
16.00-16.99	14	65	4(2)	0.24
17.00-17.99	6	61	10(5)	0.17
18.00-18.99	12	44	15(7)	0.37
19.00-19.99	10	39	9(4)	0.32
20.00-20.99	9	21	7(3)	0.48
21.00-21.99	1	15	5(2)	0.17
≥ 22.00	1	12	3(1)	0.14

TABLE 5—*Continued*

Object	Date observed	V_{obs}	Class (this work)	Previous class	$B - V$	$V - R$	$V - I$	Albedo
2009 UV18	2010-1-9	18.3	A		0.967 ± 0.094	0.520 ± 0.019	0.957 ± 0.052	
2009 XR2	2010-1-9	16.5	R		0.908 ± 0.017	0.484 ± 0.008	0.724 ± 0.031	
2010 AE30	2010-1-9	18.5	S		0.862 ± 0.090	0.461 ± 0.010	0.845 ± 0.011	

^aBus & Binzel (2002); Binzel et al. (2004)

^bTrilling et al. (2010)

^cde León et al. (2010)

^dLazzarin et al. (2005)

^eBetzler et al. (2010)

^fHicks & Somers (2010)

NOTE.—The visual magnitude V_{obs} given here is the mean value of the V -band observations. Albedos given by reference b all have uncertainties around a factor of 2.

TABLE 6
PHOTOMETRY AND CLASSIFICATION RESULTS OF OBSERVED PAIRED-ASTEROID CANDIDATES

Object	Companion	Date observed	V_{obs}	Class (this work)	$B - V$	$V - R$	$V - I$
(1979) Sakharov	(13732) Woodall	2010-1-12	18.8	S(<i>u</i>)		0.407	0.922
		2010-1-13	18.8		1.086	0.411	
(13732) Woodall	(1979) Sakharov	2010-1-10	18.7	S-like	0.864 ± 0.147	0.468 ± 0.068	
(2110) Moore-Sitterly	(44612) 1999 RP27	2010-1-10	18.4	R	0.956 ± 0.034	0.517 ± 0.033	
(4765) Wasserburg	2001 XO105	2010-1-9	16.9	R	0.852 ± 0.043	0.456 ± 0.023	0.813 ± 0.040
(5026) Martes	2005 WW113	2010-1-10	18.6	SRQV	0.863 ± 0.042	0.440 ± 0.047	
(11842) Kap'bos	(228747) 2002 VH3	2010-1-9	18.5	R	1.011 ± 0.088	0.453 ± 0.013	0.792 ± 0.027
(228747) 2002 VH3	(11842) Kap'bos	2010-1-9	18.8	S-like	0.704 ± 0.154	0.480 ± 0.057	0.829 ± 0.111
(15107) Toepperwein	2006 AL54	2010-1-10	18.5	A(<i>u</i>)	0.876 ± 0.079	0.492 ± 0.027	
		2010-1-12	18.5				1.016 ± 0.021
(25884) 2000 SQ4	(48527) 1993 LC1	2010-1-10	18.5	XT	0.709 ± 0.055	0.432 ± 0.014	
(52852) 1998 RB75	2003 SC7	2010-1-12	18.7	S	0.891 ± 0.083	0.488 ± 0.035	0.908 ± 0.079
(54041) 2000 GQ113	2002 TO134	2010-1-10	18.6	SRQ	0.871 ± 0.073	0.459 ± 0.027	
(56048) 1998 XV39	(76148) 2000 EP17	2010-1-10	17.4	R	0.874 ± 0.039	0.476 ± 0.035	
		2010-1-12	18.4				0.770 ± 0.045

NOTE.—The visual magnitude V_{obs} given here is the mean value of the V -band observations. The pairs those with both companions observed are listed in bold characters.

TABLE 8
FRACTIONAL ABUNDANCES OF EACH TAXONOMIC COMPLEX AND APPARENT C/X-LIKE:S-LIKE RATIO AS
ANALYZED FROM THE RESULTS OF SEVERAL PHOTOMETRIC/SPECTROSCOPIC STUDIES

Taxonomic complex	This work	de León et al. (2010) ^a	Michelsen et al. (2006)	Lazzarin et al. (2005)	Binzel et al. (2004) ^a	Dandy et al. (2003)	Angeli & Lazzaro (2004)
Method	Photometry	Spectroscopy	Spectroscopy	Spectroscopy	Spectroscopy	Photometry	Spectroscopy
Sample n	25	77	12	36	310	51	12
\overline{H}	17.2	16.1	15.7	17.6	17.8	17.4	14.6
A	8%	3%	0%	3%	$\sim 0\%$	0% 8%	
C	-	1%	0%	11%	7%	34% ^b	0%
D	0%	0%	8%	0%	3%	0%	0%
O	0%	4%	0%	0%	2%	0%	0%
Q	0%	25%	0%	8%	26%	25%	17%
R	28%	0%	0%	0%	$\sim 0\%$	14%	0%
S	36%	58%	92%	58%	40%	22%	58%
U	0%	0%	0%	0%	1%	0%	0%
V	0%	8%	0%	0%	5%	2%	8%
X	24% ^b	3%	0%	11%	15%	-	8%
C/X-like:S-like ratio	0.14	0.01	0.09	0.27	0.21	0.21	0.04

^aMars-crossers in the sample have been removed in this comparison.

^bThe fraction of C-complex includes the contribution from B-, C-, E- and X-complex.